

Wisconsin Highway Research Program

Repair and Strengthening of Bridge Substructures

Wisconsin Highway Research Program
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Marquette University
March 3, 2010

Summary Page

Project Title: Repair and Strengthening of Bridge Substructures

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Indirect Cost Portion at 49 %

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Research Plan

a. Background

A bridge consists of two major parts: the substructure and the superstructure. The substructure includes those parts which transfer the loads from the superstructure down to the earth. The substructure might be two abutments for a simply-supported single-span bridge. While for multi-span bridges, piers or column-supported bents are used to transmit loads to the footings and/or piles.

ASCE's Report Card for America's Infrastructure (2001) indicates that 14 percent of the bridges in the United States are rated structurally deficient or functionally obsolete because of service loads and traffic volumes that greatly exceed those expected at initial design. The primary cause of the deficiency is corrosion of the reinforcing steel. The cost to maintain the nation's bridges during the 20-year period from 1999 to 2019 is estimated to be \$5.8 billion per year, and the cost to improve and eliminate deficiencies over the same period is \$10.6 billion (ASCE 2001). A cost-of-corrosion study determines that the annual cost of corrosion to all bridges (including steel bridges) is \$8.29 billion, and this estimate does not include indirect cost incurred by the traveling public due to bridge closures (Koch et al. 2002). The cost includes the repair and maintenance for both superstructures and substructures.

The deterioration and damage to bridge substructures are common problems, for example, settlement and scour at foundations, vehicle/vessel impact, damage to pile cap, rotation of abutments resulting from un-even settlement, and so on. These problems may cause the bridge to be rated structurally deficient and have potential to threaten the safety of public. The Wisconsin Department of Transportation (WisDOT) has recognized the importance of finding effective repair methods to remedy these problems and strengthen substructures to extend the service life of the bridges. WisDOT is seeking to develop guidelines for both assessment techniques as well as recommended maintenance actions for repair activities to improve the condition for damaged or deteriorated bridge substructures.

Bridge substructures are constructed using a wide variety of materials: reinforced or prestressed concrete, steel and timber. Each material has its own unique properties and related durability considerations. There are also various repair methods including patching, concrete jackets, Fiber Reinforced Polymer (FRP) wrapping, cathodic protection to stop corrosion, etc. The following is a brief introduction to typical deterioration and repair methods for the substructures composed of concrete, steel and timber, respectively.

Reinforced and Prestressed Concrete Substructures

Reinforced and prestressed concrete are widely used for bridge construction for both superstructures and substructures. Major sources of deterioration in concrete substructures include cracking and spalling. A pier with map cracks is shown in Figure 1. The cracking in substructures can be caused by vehicle/vessel impact, chemical reaction, construction error(s), corrosion of embedded reinforcement, design error(s), freezing and thawing, foundation movement, shrinkage, and temperature changes (Army and Air Force 1994). The corrosion of

steel reinforcement can cause excessive cracking and spalling of concrete substructures as shown in Figure 2.

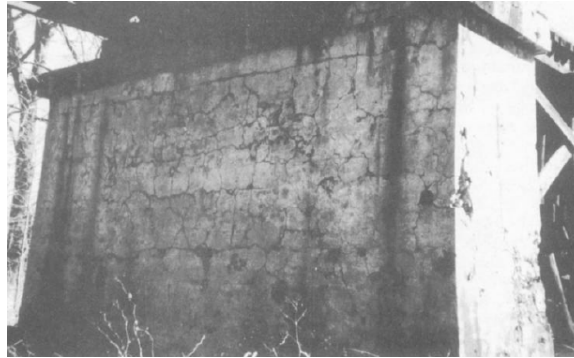


Figure 1 Map cracking in a pier (Army and Air Force 1994).



Figure 2 Corrosion of a pier column (West et al. 1999).

There are many methods for investigation and assessment of concrete substructures, including visual surveys, core drilling, laboratory tests (petrographic examination, chemical analysis, and physical analysis), nondestructive testing (rebound numbers, penetration resistance, ultrasonic pulse velocity, surface tapping, etc.), steel corrosion assessment, and load testing.

The large variety of cracking types prevents a single repair method for all concrete cracking problems. For active cracking, strengthening the structure is required to prevent further development of the cracks. For dormant cracking, simple sealing may solve the problem. Spalling is repaired primarily by removing the deteriorated concrete and replacing it with new concrete of similar characteristics (Army and Air Force 1994). Concrete jackets and fiber-reinforced polymer (FRP) wrapping can be used to repair and strengthen the deteriorated concrete substructures. Figure 3 shows FRP wrapping to retrofit a concrete pile.



Figure 3 FRP wrapping on a concrete pile (Sen and Mullins 2007).

The following methods can be used to control the steel corrosion in reinforced or prestressed concrete substructures: remove and replace all chloride-contaminated concrete; reduce the concentration of, and change the distribution of, chloride ions by using electrochemical chloride extraction; stop or slow the ingress of future chloride ions by using a less permeable cementitious overlay composed of latex, silica fume, or fly ash-modified concretes; stop or slow the ingress of future chloride ions by using sealers, membranes, and waterproofing materials; repair cracks to prevent chloride ion contamination; apply barrier coatings on the reinforcing steel in the repair areas; apply corrosion inhibitors in the repair or over the entire concrete element to either interfere with the corrosion process or modify the characteristics of the in-place concrete; and apply a cathodic protection system. Among all strategies and techniques, cathodic protection is the only technology that can directly stop further corrosion, even in the most corrosive environment, if designed, installed, and applied correctly (Sohanghpurwala 2009).

Steel Substructures

Structure steel can be used for bents, columns and piles for bridge substructures. The major deteriorations of steel substructures are rust and galvanic corrosion, cracks, buckles and kinks, and stress concentrations. Figure 4 shows a typical local buckling of pile flange. The causes for the deterioration of steel substructures are air and moisture, industrial fumes, deicing agents, seawater and mud, thermal strains or overloads, fatigue and stress concentrations, and fire (Army and Air Force 1994).

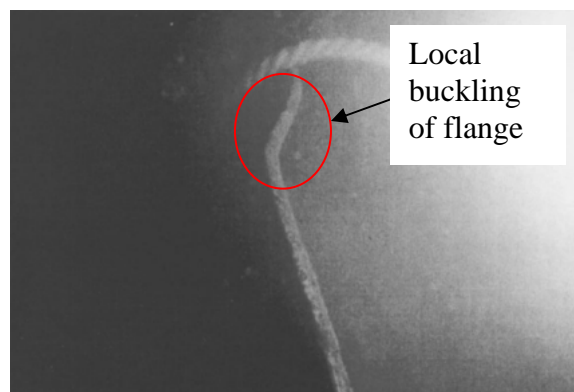


Figure 4 Underwater picture of typical local buckling of pile flange (Avent and Alawady 2005).

In addition to a close visual examination, a wide variety of nondestructive test (NDT) methods can be used to assess the deterioration of steel substructures. Dye penetration can be used to identify the location and extent of surface cracks and surface defects. Magnetic particle testing can be used to detect flaws in materials and welds, and radiography can be used to inspect steel members. A coupon can be cut from the steel substructure component and be tension tested in the laboratory to get accurate estimates for the material properties and therefore, the capacity of the steel substructure.

The most common repair strategies for steel structures involve adding metal to strengthen cross sections that have been reduced by corrosion or vehicle impact; welding or adding cover-plates to repair structural steel cracks caused by fatigue and vehicle loads; and retrofitting connections (Army and Air Force 1994). When steel piles require additional support or protection, an integral pile jacket can be placed around the steel piling. The jacket can be made by filling an FRP form with Portland-cement grout, or FRP wrapping as shown in Figure 5.

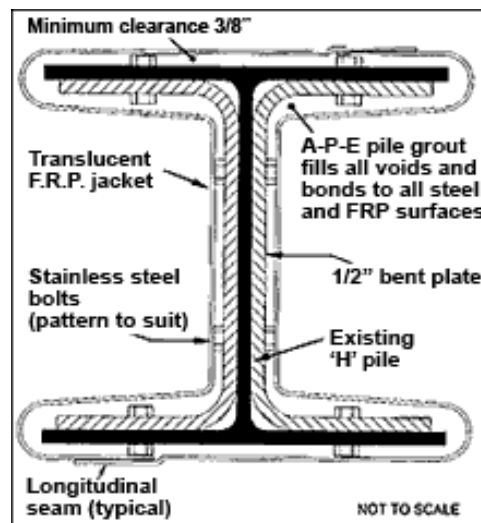


Figure 5 FRP jacket for strengthening steel pile (National Composites Network 2010).

Timber Substructures

Timber is used to build pier columns, pier caps, piles, and superstructures for bridges. If it is properly treated or protected, timber is quite durable. However, it is not a durable material in all environments. When moisture exists, wood may suffer from fungi decay as shown in Figure 6. Fungus decay can be avoided only by treatment with appropriate preservative agents. Insects may seek food and/or shelter in timber substructure components and vermin tunnels are often found in timber components in the substructure. Other deterioration scenarios found in timber substructures include weathering and warping caused by repeated dimensional changes due to repeated wetting, chemical attack, fire, abrasion and mechanical wear, collision or overloading damage, and unplugged holes (Army and Air Force 1994).



Figure 6 Wood decay in bent cap (Army and Air Force 1994).

A chipping hammer, an ice pick, and an increment borer are the primary tools used for assessment of wood deterioration. The most common repairs for timber structures are retrofitting timber connections, removing the damaged portion of the timber member and splicing in a new timber, and removing the entire member and replacing it with a new member (Army and Air Force 1994).

Deterioration of Substructures not Specific to Materials

There are several sources of deterioration and damage not specifically related to materials used in the substructures. They are abutment stability, drift and floating ice, scour, foundation settlement, and so on. Horizontal pressure from soil may exert lateral pressure on an abutment thereby causing a stability problem. Such problems can often be fixed by providing external anchorage. Drift and floating ice place forces on the piers and frame bent of bridges. They can cause structural damage to the piles or columns. A common repair to minimize this problem is to install dolphins and/or fender systems upstream of the piers (Army and Air Force 1994).

Scour is the removal geotechnical material, such as sand and rocks, from the near vicinity and beneath bridge abutments and/or piers. It can effectively reduce the bearing capacity of individual piles and pile groups, undermine pier and abutment footings, and cut into the bank. It is one of major reasons for bridge substructure failures. Therefore, when scour is detected in a bridge substructure, it must be addressed as soon as possible. Placing a tremie encasement around the bottom of the pier and injecting concrete or mortar into the encasement can make up the loss of bearing of pile due to scour (Army and Air Force 1994) and is one method of substructure repair when scour is detected (Fitch 2003). Installation of riprap (if not already present from initial construction) is another common repair method to prevent further scour at bridge abutments. Some other countermeasure systems, such as partially grouted riprap and geocontainers, articulating concrete block systems, gabion mattresses, and grout-filled mattresses, can also be used to protect bridge piers from scour (Lagasse et al. 2007).

Microbial induced corrosion (MIC) is corrosion caused or promoted by microorganisms. The prerequisite is the presence of microorganisms. The further requirements are an energy source, a carbon source, an electron donator, an electron acceptor and water (Beech et al. 2000). The kinetics of corrosion is determined by the physic-chemical environment of material surface, which can be significantly affected by the microorganisms at the surface. For example, some bacteria can significantly change the PH value of its living environment, and therefore affect

corrosion process. Microorganisms can also corrode the non-metallic material. For example, Sulphuric-acid-producing thiobacilli cause severe corrosion of concrete walls (Diercks et al. 1991).

Summary

It can be concluded from previous discussion that repairing bridge substructures is a very complex task due to large variety of construction materials, different deterioration and damage scenarios, and the variety of repair methods available. Therefore, a logical decision matrix is critical to identify effective long-term repair strategies and to select the most cost-effective method. Unfortunately, useful information on damage assessment and repair strategies is scattered and a synthesis of the state of the art is needed.

Research Objectives

The objectives of this research are to gain better and more up-to-date understanding of the deterioration and damage of bridge substructures; explore both assessment and repair strategies for bridge substructures subjected to either damage or deterioration; and develop a guideline for assessment and repair of substructures utilized by the Wisconsin Department of Transportation (WisDOT).

b. Research Approach

Work Plan

In order to achieve the objectives described in previous section, the PI's propose to complete the following tasks during the award period.

Task 1 – Review State-of-the-Art and State-of-Practice

The research team will conduct an extensive review of available U.S. and international research findings, performance data and other information related to the repair and strengthening of bridge substructures. This will include literature related to laboratory studies, field testing, analytical, and numerical models. The practice and performance data related to the assessment and repair of bridge substructures subjected to damage and/or deterioration in other state DOT's will be given special attention.

Many papers, research reports, manuals and books emphasizing bridge repair and retrofit have been published. A textbook "*Bridge and Highway Structure Rehabilitation and Repair*" authored by Khan (2010) summarizes the common sources of bridge deterioration and the corresponding repair methods. It also includes design examples and a significant number of references on this topic. Joint Departments of the Army and Air Force published a manual of "*Bridge Inspection, Maintenance, and Repair*" in 1994 (Army and Air Force 1994). All conventional repair methods for bridge substructures are discussed in detail in this manual. The American Railway Engineering and Maintenance-of-Way Association (AREMA) publishes the *Manual for Railway Engineering (MRE)* in every April. This manual contains the principles and recommended practice for railway engineering. It is a valuable source for repair of timber structure repairs. Several research efforts related to substructure deterioration and repair have been finished by National Cooperative Highway Research Program (NCHRP) (Lagasse et al. 2007; Sohaghpurwala 2009) and other state DOT's (West et al. 1999; Fitch 2003). Currently,

there are also on-going research activities related to bridge substructure repair, such as NCHRP sponsored research of “Underwater Fiber-Reinforced Polymer Repair of Corroding Piles Incorporating Cathodic Protection” and Pennsylvania Department of Transportation sponsored research of “District 3-0 Investigation of Fiber Wrap Technology for Bridge Repair and Rehabilitation”. The research team will use these documents and other references listed in the section of References in this proposal as a starting point for this task. This task will culminate with a synthesis of the review findings.

Task 2 – Survey of State DOT’s

The research team will conduct a survey of State DOT’s with similar climate and geologic/geotechnical characteristics. At a minimum, the states of North Dakota, South Dakota, Minnesota, Iowa, Illinois and Michigan will be contacted and/or surveyed. Other states, such as Pennsylvania, and provinces in Canada with similar latitude as Wisconsin will be contacted. The survey will be limited to major substructure deterioration conditions (e.g. scour, spalling, and fungal rotting), the assessment practices used to detect sources of major deterioration, repair techniques employed, the effectiveness of these repair strategies in those states or provinces, and the cost to employ the repair or retrofit strategy.

Some sample questions for the state of practice survey will include questions such as those below (and others developed through the research effort):

- What are the major substructure deterioration problems encountered in your state?
- Which investigation method(s) is used to identify sources of substructure deterioration?
- What techniques are commonly used to repair deteriorated or damaged substructures?
- What is the most effective repair technique for (specific) problem in your state?
- What are the typical costs for the repair techniques used?
- What are the relative costs for the repair techniques used (cost of one repair technique relative to another)?

The state of practice survey to be employed by the research team will be drafted in a manner that is similar (if not identical) to those used by researchers in NCHRP-sponsored research efforts. Determining costs for retrofit techniques will demand that the research team be able to obtain cost information for the repair strategies employed. It is envisioned that gaining this information will be a challenge, but it is anticipated that maintenance engineering staff at other regional DOT's will release this data to the research team. If this data is not readily available to the research team, or it is not available, the research team will develop construction sequence maps that will allow the team to develop cost metrics for each retrofit strategy relative to one another. In this way, the research team may not be able to determine exact cost to implement each retrofit strategy, but they will be able to determine how much more or less one strategy is likely to be relative to another. Establishing the effectiveness of the retrofit strategy over time will be admittedly very, very difficult in the absence of actual data. In the absence of data related to actual long-term performance of a retrofit strategy, the research team will be forced to develop rational estimates for long-term effectiveness. It is envisioned that this activity will be done with consultation of WisDOT maintenance engineering staff and maintenance staff of other state DOT's. The effectiveness of the strategy employed can then be used to perform a relative cost-benefit analysis of each retrofit/repair approach.

The research team will work with WisDOT regional bridge engineers to identify several bridges with typical deterioration conditions in Wisconsin. The research team will visit these bridges to investigate and document the deterioration and damage. In cases where deterioration would require sub-surface investigation (e.g. scour), the research team will make appropriate contact with consultants responsible for determining the extent of deterioration in these substructure systems for photos and/or reports to aid in documenting the deterioration present (e.g. Collins Engineers, Inc.). For each type of deterioration or damage condition, the research team will contact bridge contractors and other companies specializing in repair/retrofit to find repair techniques that have been employed. These techniques will be closely evaluated for effectiveness, durability, and cost to find the optimal method for certain deterioration or damage scenarios. It is expected that state bridge maintenance personnel will be sources of cost information for repair strategies. Based on the information provided by WHRP and the oversight committee for this project, the following regional bridge maintenance engineers have been identified as potential sources of bridge repair information:

SE Region:	John Bolka
SW Region – Madison:	Matt Murphy
SW Region – LaCrosse:	Dave Bohnsack
NE Region:	Dale Weber
NC Region – Rhinelander:	Brock Gehrig
NC Region – Rapids:	Thomas Hardinger
NW Region – Eau Claire:	Greg Haig
NW Region – Superior:	Al Bjorklund

During the preparation of this proposal, the PI's have contacted four of these regional engineers to seek if it is possible to get help from them to collect past and future substructure repair strategies and cost if the present proposal is funded. At the time this proposal was submitted, two of them responded and agreed to help with the research effort. The northwest region is planning to repair two bridges by wrapping columns using FRP this year. This repair project can be used as an example to study the effectiveness and cost of FRP wrapping in the scope of this proposed research. If this research proposal is funded, the research team will contact all of these engineers to collect any and all the data related to cost and effectiveness for previous and all data related to current substructure repair projects. If it is permitted, the research team will also attend the annual structures maintenance meeting to present this research and seek feedback from other attendees at the meeting.

The completion of this task will provide a summary of deterioration problems, commonly used assessment practices, repair techniques, and relative costs to implement repair strategies for a Wisconsin cohort of state DOT's and the state of Wisconsin itself. Recommendations for assessment and repair techniques for repairing substructures in Wisconsin will be provided as a result of appropriate cost-benefit analyses implemented.

Task 3 – Interim Report

Near the end of first half of the research period of this project, the research team will write an interim report to summarize the key findings of Tasks 1 and 2. The research team will also make

an interim presentation to the oversight committee if it is required. The interim report and presentation will provide a basis of discussion between the research team and the project oversight committee to indentify the key tasks which should be performed in the second half of the research period.

Task 4 – Develop a Guidebook

By using the findings from previous tasks, a guidebook will be developed for WisDOT. This guidebook will summarize the common deterioration and damage problems in bridge substructures in Wisconsin and other cohort states and repair techniques available for these problems. For each repair technique, a detail drawing for a typical situation will be provided. A decision matrix will be provided to find the most appropriate repair method for specific problems. The decision will be based on the effectiveness, durability, and cost to implement the repair method.

Task 5 – Indentify Future Research

In order to evaluate the effectiveness or durability of specific repair technique, field and laboratory tests, or numerical and analytical models may be required as future investigations. For example, half-cell potential test can be used to evaluate reinforcement corrosion before and after cathodic protection is applied to the substructure. Finite element analysis can be used to study the effectives of FRP wrapping for a column or pile. In-field load tests can be performed before and after strengthening the bridge substructures to evaluate its improvement of stiffness. The completion of this task will provide recommendations for future research to expand the findings of this project.

Task 6 – Submit Draft Final Report and Present Findings to TOC

At 15 months after the project start (3 months before the end of contract), the research team will submit the draft final report to TOC for review. Presentation of final findings will also be given to TOC in this period.

Task 7 – Revise and Submit Final Report

After the research team is provided comments on the report from the oversight committee, the report will be revised to address the comments. A final report will be submitted to the Wisconsin Highway Research Program for distribution through their research library. It is also expected that the researchers will present their findings at annual meetings of the Transportation Research Board, and other related national and international conferences.

Expected Contribution from WisDOT Staff

The WisDOT regional bridge engineers will be contacted to indentify several bridges with typical deteriorations in Wisconsin. The research team will also need help from WisDOT personnel to collect cost information related to previous repair and strengthening projects for bridge substructures. The information includes, but is not limited to, type of deterioration, repair technique, cost, and performance after the repair.

c. Anticipated Research Results and Implementation Plan

When this research project is completed, the proposed research efforts will generate the following outcomes for WisDOT:

- a literature review and synthesis of other state DOT's practice and recent research in the area of repair and strengthening of bridge substructures;
- a summary of deterioration problems, and commonly used assessment practices and repair techniques of other state DOT's;
- a decision matrix to find optimal repair method for specific problem;
- a guidebook for WisDOT to select assessment and repair technique for the deteriorated or damaged substructure including the decision matrix referenced above;
- recommendations with regard to potential future studies to expand the findings of this project.

There is an immediate avenue for implementation of the information generated through the completed research effort. The guidebook developed in this research will help WisDOT bridge maintenance and bridge engineers select optimal technique to repair a deteriorated or damaged bridge substructure components.

Some repair techniques may be (at best) theoretically applicable for certain deterioration problems. Furthermore, it is possible that local companies may not be familiar with the specific retrofit technique that has successfully been used by another state DOT. This might be a potential impediment to the full implementation of the findings of this research. In order to successfully implement the findings, the guidebook and decision matrix should be used and evaluated within the context of actual substructure repair projects. In other words, the full benefit of the research effort might require that some repair or retrofit techniques be tried and evaluated (for effectiveness and cost) moving forward after the research is completed. The success or failure of these novel approaches can then be used to back-feed the decision matrix and make modifications. As a result, the research effort can also be characterized as a skeletal framework for evaluating retrofit/repair methods and establishing an ever-growing guidebook of these techniques.

d. References

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Time Requirement

A tentative schedule has been developed for the proposed research effort. It includes the seven tasks discussed earlier in the detailed work plan:

- Task 1** Review of State-Of-The-Art and State-Of-Practice
- Task 2** Survey of State DOT's
- Task 3** Interim Report
- Task 4** Develop a Guidebook
- Task 5** Indentify Future Research
- Task 6** Write and Submit Draft Final Report and Present Findings to TOC
- Task 7** Revise and Submit Final Report

A timeline for completion of each task is given in Table 1 and summary of hours is given in Table 2.

Table 1: Phasing of Tasks during the 18 Months of Research Period from October 2010.

Task	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
	Fiscal Year 1												Fiscal Year 2					
1																		
2																		
3																		
4																		
5																		
6																		
7																		

Table 2: Summary of Hours.

INDIVIDUALS	TASKS							TOTAL HOURS
	1	2	3	4	5	6	7	
Principal Investigator	8	12	40	50	8	45	7	170
Co-Investigator	8	12	40	50	8	45	7	170
Graduate Students/Senior Staff	300	200	100	100	100	100	100	1000
Hourly Students/Junior Staff								0
Office Staff								0
TOTALS	317	226	183	204	121	196	121	1368